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Spread Spectrum Series, Part Four

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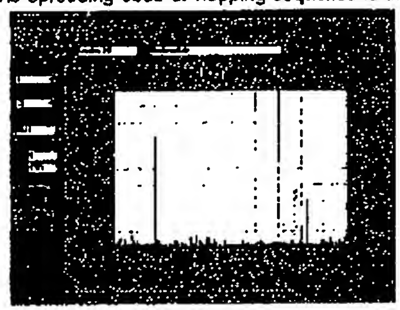
The most critical aspect of a spread spectrum design is synchronization The first part of synchronization is to acquire the signal from the transmitter. In a direct sequence system the spreading codes generated in the receiver must be aligned to the desired incoming signal. In a frequency hopping system the receiver must jump to the same frequency at the same time as the desired incoming signal The system component of a spread spectrum receiver that finds the proper alignment of the spreading code or hopping sequence is known as the "searcher".



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Many IS-95 base stations can be seen in this measurement of correlated power vs code phase taken with an Super Eagle CDMA Pilot scanner by Berkeley Varitronics Systems, Inc.

Although frequency hopping searchers and direct sequence searchers are conceptually similar, each presents different areas of difficulty. In general, direct sequence searchers are more complicated and have many more design challenges For this reason, this article will be primarily concerned with the design of direct sequence searchers and will finish with a brief discussion of the techniques used in frequency hopping searchers

Direct Sequence Searchers

Direct sequence spread spectrum (DSSS) transmitters "spread" a narrow band information signal across a wide band of frequencies using a spreading code. These codes are sufficiently random to have the noise like property of a flat spectrum, but are deterministic and can be recreated at the receiver These codes only correlate well to time aligned version of the same code. That is to say, if two copies of the same spreading code are misaligned, they have a weak correlation and if they are aligned they have a strong correlation. This property allows a searcher to determine when spreading codes are aligned.

2/5

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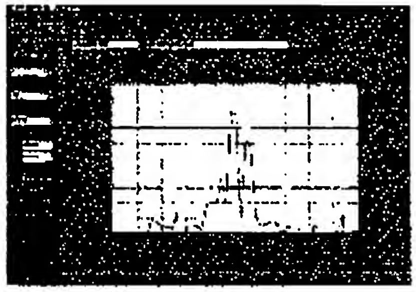

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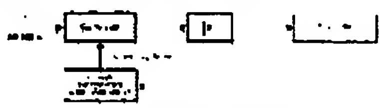
An IS-95 signal with multipath causing correlated power to arrive at different code phases viewed with an Super Eagle CDMA Pilot scanner by Berkeley Varitronics Systems, Inc.

In order to explain some of the terminology used in DSSS searcher design, consider two code generators, both running at the same frequency and both producing the same spreading code. The output bits of a code generator are often called chips, to distinguish them from the slower rate data bits. Choose some chip in the code to be called the start of the sequence. If both code generators produce the start chip at the same time, the code generators are said to be aligned or in phase. All other alignments are said to be out of phase. Changing the phase of a code generator refers to changing the alignment of the generator with respect to a reference generator running at exactly the right frequency, that is to say, the transmitter frequency.

All direct sequence spread spectrum systems provide some method of obtaining alignment of the arriving signal (or one of the arriving signals) and the spreading code at the receiver. In code division multiple access (CDMA) systems, a separate code channel, known as the "pilot channel", is usually used to transmit the spreading code without any data. This channel can be used by the searcher to find the proper alignment of the code at the receiver. In non-CDMA systems, alternative approaches can be used to disregard the modulated data and consider only the spreading code. The practical differences between these two types of systems will be discussed as they present themselves.

In general, a searcher is not only responsible for finding the proper alignment to one arriving signal, but for finding and managing the alignment of a number of arriving signals. A received signal may contain several, time shifted signals spread with the same code. Multipath reflections may cause time-shifted copies of the same signal to arrive at the receiver. In addition, some CDMA systems use time shifted spreading codes to separate different transmitted signals. This approach is used to separate base stations in IS-95.



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A typical DSSS Searcher

A generic DSSS searcher is shown in Figure 3. The phase controllable code generator produces the spreading code for the system. The ability to control the phase (or alignment) of this code generator is the heart and sole of the searcher. The design of this code generator defines the performance of the searcher and restricts the available algorithms. The correlator compares the output of the code generator to the input signal and produces a signal proportional to the match. The magnitude of this signal is used to decide if the input signal is in phase with the searcher's code generator. The correlator and magnitude functions are often considered as a single block called a "power calculator". The control block is usually a microprocessor, although it can be implemented directly in hardware as well.

A typical implementation of a power calculator is shown in Figure 4. The spreading code from the searcher's phase controllable code generator is correlated against both the in phase and quadrature components of the base band

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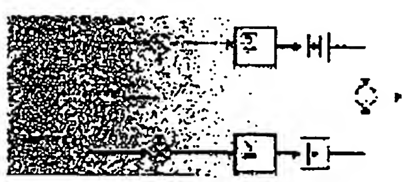
signal This allows the power calculator to work in a non-coherent radio, because it detects the spreading code regardless of the RF phase. However, the length of the correlation is restricted by how close the transmitter and receiver are allowed to differ in frequency before synchronization. The correlation time must be small compared to the period of the phase rotation or the correlated signal will be averaged out There is a further restriction on systems that do not have a dedicated pilot channel. In these systems, the correlators work with a spreading code that has been modulated with data, so the correlation time must be equal to or less then a symbol period, so that the data modulation does not average out the correlation. The correlation must also be timed to start and end on symbol boundaries, to insure that the modulating data remains constant during the calculations The squaring circuits shown if Figure 4 insure that the output of the correlator is the same magnitude regardless of phase rotation In practice, these are often replaced by absolute values to minimize the hardware complexity. In many applications the degradation in performance with this technique is acceptable.

A typical searcher algorithm would try all possible phases of the searcher's code generator and measure the output of the power calculator. The principle question in searcher design is, "How long does it take to do the search?" If the search takes too long, the difference in clock frequencies between the receiver and transmitter may move the phase alignment away from the position that it was found in. In such cases, the search is generally repeated using a window around the phase that was detected in the first search. In fact, a series of narrowing windows is often used. When the spreading code is long and the search time is slow, the real time it takes to search may be prohibitive for the application Search times in the minutes are not uncommon in designs. Three factors determine the search time the method of phase control used in the code generator, the length of the code and amount of hardware redundancy

There are three main types of phase controllable code generators The simplest of these is a code generator that is clocked at a slightly different frequency than the transmitter's generator. This generator will slowly drift through all phase alignments of the code. Since this phase shift is continuous, it changes during the correlation time and must be kept to a slow enough rate to maintain good correlation results. The advantage of this approach is simplicity. This type of generator will be referred to as a "sliding generator".

Another type of generator that is conceptually similar is a code generator that can be stepped digitally by one phase. This generator runs on the same clock as the code generator of the transmitter, but can skip or hold a chip in the code This type of generator is far more powerful than the sliding generator and will be referred to as a "stepping generator" A variant that has an obvious advantage is a generator that can both retard and advance the phase of the code. A stepping generator can be advanced by a series of steps to a desired phase of the code before any correlations are performed This is the minimum of flexibility that is needed to perform the previously mentioned narrowing search window algorithm. Also, since the phase changes in discrete steps, the code phase is not changing during the correlation. This improves the correlation results and usually results in shorter search times, since phase movement during the correlation does not restrict the search speed.

The last type of generator is one that can rapidly jump to any code phase. This generator has an obvious advantage over the others mentioned and warrants further discussion This type of generator will be referred to as a "jumping generator" The implementation of these generators is less obvious and often requires some innovation. In fact, Berkeley Varitronics Systems, Inc. has a few patents pending on the design of this type of code generator. For codes that can be created with a linear feedback shift register, the process is well known and requires a minimum of hardware. The difficulty arises with other codes. For instance, the spreading codes for IS-95 were created starting with codes that can be generated with a linear feedback shift register and adding one zero to the sequence. The addition of that zero no longer allows the simple phase changing hardware used in linear feedback shift registers to be used. For a reasonable sized code, the code could be placed in ROM and addressed with a counter and an adder, although this approach usually consumes much more real estate than more creative alternatives



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A typical power calculator design

4/5

The true advantage of a jumping generator can only be seen in the context of searcher algorithms. To illustrate a point, the searcher in an IS-95 handset will be used as an example. The base stations in IS-95 transmit a pilot code with a length of 32,768 chips with a frequency of 1,228,800 chips/sec. The start of this code sequence is sychnonized to GPS time and each base station starts its pilot at a different time offset. To a searcher in the handset, the signal from each base station arrives at a different phase. Once an initial base is found, the searcher quickly searches small windows around possible locations of other base stations, so that it can quickly locate new base stations as the handset is moved around. If the searcher had to search each code phase with correlation length of 256 chips using a single power calculator, it would take almost seven seconds to complete one search. This is because the searcher must remain in each code phase for at least 256 chips to perform the correlation and there are 32,768 phases. If, on the other hand, the searcher was to search a window of 16 chips around 20 locations, the total time for that search is about 70ms. In this case, a jumping generator is required to provide timely updates for possible handoffs.

Redundant hardware is another option to help reduce the search time. Consider a searcher that has four power calculators that measure power at different code phases. This searcher will search almost four times as fast. Most of the time in a searcher algorithm is spent waiting for power calculations or advancing a code generator. As a practical matter, only the power calculators are redundant. A single code generator can be used with an addition chip delay for each power calculator.

Another approach to faster searching is to vary the correlation length. This method correlates for a given number of chips and compares the result to a threshold. If the correlation result exceeds the threshold, the correlation is continued for longer. If not, the correlation ends and the phase is advanced. Since most of the phases do not have correlated power, this usually results in a much faster search.

At this point, it should be noted that the correlation length determines the processing gain of the search. For a correlation length of 255 chips, the minimum spreading code that can be detected is 24 dB below the total energy in the receiver bandwidth. This assumes that the correlation is performed across a multiple of the spreading code length and that the spreading code has very good autocorrelation properties. If the code length is longer than the correlation length, partial correlation noise is introduced. A subsection of a spreading code will generally have a substantial correlation to other sections of the same code. For large code length to correlation length ratios, the partial correlation noise is the dominating factor in determining the needed processing gain and thus the needed correlation length.

Frequency Hopping Searchers

Frequency hopping spread spectrum (FHSS) systems transmit a relatively narrow bandwidth signal on a particular channel for a period of time, known as the dwell time, and then change to a different channel. The order of channels that are used is known as the hopping sequence. Hopping sequences are chosen to evenly use the spectrum available and to have a minimum of collisions with other hopping sequences in use. FHSS searchers use the presence of demodulated data on a channel to determine if the searcher is aligned to the hopping sequence of the transmitter.

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Correlation results with two different correlation lengths

A FHSS searcher can use an algorithm similar to a DSSS searcher. If the searcher hops the sequence at a different rate than the transmitter, it will eventually align with the transmitter and be able to demodulate data. In many frequency hopping systems, the hop sequences are relatively short due to a limited number of channels. In these cases, it is often more efficient to set the receiver on a single channel and wait until the transmitter sequence

5/5

lands on that channel and then pick up the sequence from there. In practice, the receiver would have to slowly change channels if it did not detect the transmitter incase the chosen channel happened to have a strong interferer.

A frequency hopping IEEE 802.11 transmitter hops 79 channels (for the North America and Most of Europe region). The hopping sequences are 79 hops long with a dwell time of approximately 20ms (this is a typical value). A searcher for IEEE 802.11 can go to any channel in the band and simply wait for approximately 1.6 seconds for the detection of the signal from the transmitter. In a wireless local area network (WLAN) this is certainly a reasonable synchronization time. In the case of IEEE 802.11, an access point transmits synchronization information, such as the hop sequence and dwell time, every time it hops to a new frequency.

Conclusions

The trade off in searcher design is always searcher speed for design complexity. This is particularly pronounced in DSSS systems, where the solution to shorter search times involves the design of jumping generators and multiple power calculators. The most straightforward approaches to speeding searcher designs tend to hog real estate and the more elegant solutions require expertise and design time.

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